CONVENERS' HIGHLIGHTS: NUCLEAR FORCES AND STRUCTURE, NUCLEON-NUCLEON CORRELATIONS, AND THE EMC EFFECT

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Nuclear EMC Effect and Short Range Correlations (SRC)

New, unexplained dynamics in the nuclear environment

David Gaskell  The EMC Effect

- 35 years of inclusive experiments have provided a lot of information about the properties of the EMC Effect
- No consensus on origin

- New several avenues of investigation
  - Connection with Short Range Correlations
  - Tagged measurements
  - Flavor dependence (valence)
  - EMC effect in polarized quark distributions
  - Sea quarks

There are a lot of interesting new ideas and there will soon be a lot of new data with which to test these new ideas.
NEW RESULTS: SRCs & EMC EFFECT

Several results shown from data mining of CLAS eg6 data set (nuclear targets)

Study \((e,e')\) Data from the CLAS6 Detector at JLab

Our New EMC Effect Measurements

Our New SRC \(a_2(A/d)\) Measurements

Paul Reimer, Argonne National Laboratory
ASSUME THAT SRC ACTS AS ‘MEASURE’ OF EMC EFFECT AND THAT SRCS (AND EMC) ARE DOMINATED BY NP PAIRS

\[
F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)
\]

**Or Hen - MIT**

**Barak Schmookler - MIT**
3N-SRCS?

CLAS showed second plateau beyond x=2
• Significant bin migration corrections due to modest momentum resolution

JLab E02-019 [Hall C] – much higher ratio at x>2; higher $Q^2$
• Poor statistics

No real test for 3N-SRCs in inclusive scattering
E08-014 RESULTS

Consistent within uncertainties of E02-019; well above CLAS ratios

- $Q^2$ values near CLAS data, so not a $Q^2$ dependence

Ratio increases above $x=2$, but does not show plateau

- Scaling prediction for 3N-SRCs not valid in this $x$, $Q^2$ range Why?

Kinematics ($x$, $Q^2$) may not be sufficient to isolate 3N-SRCs

- Don’t know what $x_{\text{min}}$ is required for plateau to begin at any given $Q^2$
  - Don’t have a clear momentum threshold for 2N-SRCs to be negligible, as opposed to 2N-SRCs while MF contributions fall dramatically beyond $k_{\text{Fermi}}$

- Motion of 3N-SRCs has large effect near kinematic endpoint ($x \approx 3$); much worse than for deuteron

John Arrington,
Zhihong Ye - ANL
NEW ANALYSIS OF E02-019 DATA

Assume 3N region shows plateau; extract $a_3$ (relative contribution of 3N-SRCs)

$A_3$ is proportional to $(a_2)^2$; expected if 2N-SRCs proportional to density and 3N-SRCs proportional to $(\text{density})^2$

$a_2$ = relative likelihood of nucleon to be in a high momentum nucleon pair
**Inclusive SRC (and EMC) Measurements: JLab@12 GeV**

**EMC effect at 12 GeV**
[E10-008: JA, A. Daniel, D. Gaskell]

**SRC Isospin dependence: $^3$H vs $^3$He**
E12-11-112 (e,e'), E12-14-011 (e,e' p)
$^3$H, $^3$He DIS: EMC effect and $d(x)/u(x)$
Charge radius difference: $^3$He - $^3$H
Lambda hypernuclei from $^3$H

** SRCs at x>1 at 12 GeV**
[E06-105: JA, D. Day, N. Fomin, P. Solvignon]

**Full $^3$H, $^3$He program (5 expts) in 2018 (Hall A)**
Initial set of light nuclei in 2018 (Hall C)
Hall A 2018 Spring Tritium Run

1. **MARATHON**
   - Inclusive deep-inelastic scattering: $d/u$ ratio

2. $(e, e'p)$ Experiment
   - Coincident quasielastic proton knock-out

3. $x_B < 3$ Experiment
   - Inclusive scattering in the $1 < x_B < 3$

Still to come in Fall Run

1. $x_B < 3$ continued …
   - Investigation of $x > 1$ and $x > 2$ regions

2. $x_B = 3$ Experiment
   - Elastic form factors of the triton.

3. Hypernucleus Experiment
   - $\Lambda n$ interaction via $^3H(e, e'K^+)$

Sealed-cell gas target
$^3$He(e, e' p)/$^3$H(e, e' p) ratios

Map out transition from $R \approx 2$ (proton counting) at low missing momentum to $R \approx 1$ (np-SRC dominance) at high missing momentum

Very preliminary (online) results show accumulated statistics
**MARATHON - D(X)/U(X)**

\[
\frac{F^p_2}{F^n_2} = \frac{2\mathcal{R} - F^3\text{He}_2 / F^3\text{H}_2}{2F^3\text{He}_2 / F^3\text{H}_2 - \mathcal{R}}
\]

Ratio of proton to neutron depends only on ratio of nuclear effects in \(^3\text{He}\) and \(^3\text{H}\)

Avoids large model dependence associated with extraction from D/p
MARATHON - D(X)/U(X)

\[
\frac{F_2^p}{F_2^n} = \frac{2R - F_2^3\text{He}/F_2^3\text{H}}{2F_2^3\text{He}/F_2^3\text{H} - R}
\]

Ratio of proton to neutron depends only on ratio of nuclear effects in \(^3\text{He}\) and \(^3\text{H}\)

Points show statistical uncertainties based on spring 2018 data taking

Avoids large model dependence associated with extraction from D/p

Current uncertainty

MARATHON projected uncertainty
The ALERT experimental run-group
A comprehensive program to study nuclear effects

**Nuclear GPDs**

\[ {}^4\text{He}(e, e' \gamma) {}^4\text{He} \]
\[ {}^4\text{He}(e, e' \gamma) {}^4\text{He} \]

Directly compare quark and gluon radii

**Tagged EMC**

\[ {}^4\text{He}(e, e' + {}^3\text{H} )X \]
\[ {}^4\text{He}(e, e' + {}^3\text{He})X \]
\[ {}^2\text{H}(e, e' + p )X \]

Address key questions about the EMC effect

**Tagged DVCS**

\[ {}^4\text{He}(e, e' \gamma p + {}^3\text{H} ) \]
\[ {}^4\text{He}(e, e' \gamma + {}^3\text{He})n \]
\[ {}^2\text{H}(e, e' \gamma + p )n \]

Connect partonic and nucleonic modification

**ALERT requirements**

- Identify light ions: H, \(^2\)H, \(^3\)H, \(^3\)He, and \(^4\)He
- Detect the lowest momentum possible (close to beamline)
- Handle high rates
- Provide independent trigger
- Survive high radiation environment
  → high luminosity
Test FSI models for different spectator kinematics with high precision

Separate EMC effect from low-momentum (mean-field) nucleons and high-momentum SRCs

Q^2-rescaling and x-rescaling as examples of models with very different dependence on recoil momentum

Directly compare quark, gluon radii
COLOR TRANSPARENCY AND THE EMC EFFECT; OVERVIEW, PLANS, AND FIRST HALL C DATA TAKING

Spring 2018:
- SHMS optics commissioning
- Detector checkout, calibration
- F2 of proton, deuteron
- Color Transparency in $^{12}$C(e,e'p)
- EMC effect in $^9$Be, $^{10,11}$B, $^{12}$C

SHMS Detector System

Eric Pooser – JLab
Dipangkar Dutta – MSU
Holly Szumila-Vance – JLab
Dave Gaskell – JLab [plenary]
COLOR TRANSPARENCY; new Hall C data

Reach Proton momenta where BNL saw large effect in (p,2p)

Kinematics and uncertainties from spring data taking

Dipangkar Dutta – MSU
Holly Szumila-Vance – JLab
May 29, 2018
Astronomers Spot a Distant and Lonely Neutron Star
Nuclear-Matter Equation of State from Chiral Effective Field Theory

Fits to saturation region

Christian Drischler

CD, Hebeler, Schwenk, arXiv:1710.08220

Neutron and symmetric matter with consistent NN + 3N forces

- 4N HF energy \(\sim 150\) keV @ \(n_0\)
- narrow ranges for \(E_{\text{sym}}\) and \(L\)
- uncertainties from chiral EFT

Epelbaum et al., EPJ A 51, 53

Symmetric matter @ \(N^3\)LO:

- reduced cutoff dependence
- reduced theo. uncertainties

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<tr>
<th>(\Lambda/c_D) [MeV]/[1]</th>
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May 29, 2018 | CIPANP 2018: Palm Springs | Christian Drischler | 12
RITU KANUNGO: CONSTRAINING THE NUCLEAR FORCE WITH RARE ISOTOPES

$^{10}\text{C}(p,p)$: Constraining the nuclear force via dynamics @ drip-line

Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with $^{10}\text{C}$

A. Kumar, R. Kanungo, A. Calci, P. Navratil et al.

$^{10}\text{C}(p,p)$ elastic scattering angular distribution exhibits strong sensitivity to constrain various prescriptions of the nuclear forces from chiral EFT.
Tidal deformability, $\Lambda$, is not sensitive to measured sub-saturation constraints.

At high density, pressure $P$ and $\Lambda$ are strongly correlated. $P$ can be determined from heavy ion experiments.
Neutron skin thickness is strongly correlated with a myriad of neutron-star observables: neutron-star radii, crust-core transition properties, cooling observations, pulsar glitches, moments of inertia, and tidal polarizabilities. Experimental measurement of the *neutron skin thickness* in conjunction with the astrophysical and gravitational wave observation of *neutron star properties* can be used to constrain the nuclear equation of state under extreme conditions.
NEUTRON SKIN

PREX-II - $^{208}\text{Pb}$

- Aims to each goal of $\delta R_n \sim 0.06$ fm
- Improved shielding and more advanced targets allow for full running
- Will provide reliable constraints on slope of symmetry energy

CREX - $^{48}\text{Ca}$

- Measurements on $^{48}\text{Ca}$ to 0.02 fm
- Gives broader reach over periodic table
- Contributing systematics slightly different
- $A \sim 40$ now within reach of microscopic calculations

Scheduled for Summer 2019
Nuclear Hamiltonian:
- derivation of contributions up to $N^3$LO completed already in 2011; derivation of $N^4$LO corrections done for $V_{2N}$ and almost done for $V_{3N}$ (new LECs…) and $V_{4N}$
- accurate & precise 2N potentials at $N^4$LO are available,
- promising results for few-N systems based on 2NF + 3NF@$N^2$LO [LENPIC]

Electroweak current operators:
- have been worked out completely to $N^3$LO
- some $\pi N$ LECs in $1\pi$ axial charge at $N^3$LO are unknown…
  [lattice QCD? $v$-induced $\pi$-production? resonance saturation? large-$N_C$?…]
Tremendous growth of ab-initio progress recent years
Agreement between different ab-initio methods now possible for medium-mass nuclei
Poor saturation properties of existing chiral EFT interactions clear in heavier systems

Stroberg et al., PRL (2017)
One approach is **diagonalization of the Hamiltonian in a basis**. Modern techniques and computers can handle up to ~ 25 billion basis states (though that is is not the primarily measure of computational burden) and there are many promising techniques for extending the reach and accuracy of *ab initio* calculations (e.g., Machine learning)

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**Machine learning**

*From Negoita et al, arXiv:1803.03215* 

**Extrapolation via Artificial Neural Net (ANN)**

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**Figure 7. Comparison of the NCSM calculated and the corresponding ANN predicted gs energy values of $^6$Li as a function of $\hbar \Omega$ at $N_{\text{max}} = 12, 14, 16$, and 18. The lowest horizontal line corresponds to the ANN nearly converged result at $N_{\text{max}} = 70$.**
Alan Wuosmaa: Experimental tests of ab-initio structure calculations

- Many Successes
  - Binding and excitation energies
  - Charge and matter radii
  - Spectroscopic overlaps / spectroscopic factors
  - Transition matrix elements
  - Continuum states

More challenging for theory

$^{10}\text{B}(\rho,\rho')^{10}\text{B}^*$ in HELIOS at ANL

The discrepancy remains for GFMC in $^{10}\text{B}$

- New results favor a smaller $\alpha$ branch, reduce combined uncertainty
- Uncertainty in B(E2) now dominated by 0.16% gamma-ray branching ratio

Kuvin et al., PRC 96, 041301(R) (2017)
Ushasi Datta: Weakly bound neutron-rich nuclei and cosmic phenomena

First Direct evidence of multi particle-hole ground state of $^{33}$Mg

Threshold strength---direct breakup-----quantum numbers with spectroscopic factor $^{41}$Ca (7/2-) $^{33}$Mg(3/2-)


$^{32}$Mg(0, gr) $\otimes$ $\nu$ p3/2  Yordanov et al., PRL 104(2010) magnetic moment~ - 0.86 $\mu_N$, expt.- 0.745 $\mu_N$

$^{32}$Mg(3.5, 1-) $\otimes$ $\nu$ s1/2

$^{32}$Mg(2.5, 2 +) $\otimes$ p3/2

$^{\nu}[200]$ ~ 60-70% j1/2

Larry et al, PLB23(1966) explained similar observation by deformed core
1st quantum computation of the deuteron

Eugene Dumitresco: Cloud Quantum Computing of an Atomic Nucleus
NFS #8
The reduction of spectroscopic strength...may indicate correlations beyond effective interaction theory and limited model spaces.

- Minority nucleons are more correlated than the majority species
- These correlations are not captured in effective shell-model

From the asymmetry dependence of the reduction and consistent with expectations from some models of nuclei and nuclear matter, the minority nucleons in an asymmetric nucleus are more correlated than the majority nucleon species. This agrees with the large body of work on SRC from JLab by Hen, Weinstein et al.